Computers & Industrial Engineering 157 (2021) 107300

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

An integrated production-logistics-crop rotation planning model for sugar beet supply chains

I. Fikry [a,b,*], Mohamed Gheith [a,c], Amr Eltawil [a,c]

[a] Department of Industrial and Manufacturing Engineering, Egypt-Japan University of Science and Technology, Alexandria, Egypt
[b] Design and Production Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt
[c] Production Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

ARTICLE INFO

Keywords:
Agro-food supply chain
Agricultural planning
Crop rotation planning
Linear programming

ABSTRACT

This paper presents an integrated strategic-tactical planning model for the sugar beet supply chain problem. The model includes the critical agricultural and industrial decisions coupled with the transportation of crops by capacitated vehicles from farms to the processing facilities. In the agricultural stage, the proposed model is used to analyze both agronomic and operational constraints for achieving a sustainable farming system through feasible strategic crop rotation plans. These plans integrate crop sequences with temporal and spatial variations while considering the known seasonal demand. The agricultural decisions involve crops planting and harvesting decisions to fulfill both fresh produce crops and processing demands. In the industrial stage, the key decisions include aggregate production plans for processing the harvested beet, as well as managing the shipping and storage of these agro-materials in the production facility. In this paper, a binary integer programming model is formulated with the objective of minimizing the overall operational cost including transportation and inventory of processed and non-processed beets. A unique time dimension was added to the planning horizon to allow crop rotation planning between different cropping seasons. A realistic case is used to test the formulated model and elaborate its complexity.

1. Introduction

The major concern of agro-food supply chains is the transformation of crops into unprocessed and processed products. Generally, an agro-food supply chain includes many activities starting with cultivating the planned crops, harvesting of the crops on the appropriate time based on crops' maturation, and finally delivering the final processed/fresh products to the customers. Improper planning results in waste along the supply chain and affects the profitability and the deterioration of crops quality.

One of the important issues that should be considered in an agro-food supply chain is the cropping decisions. Cropping decisions include but not limited to: the decisions related to the allocation of plots (i.e. the area for cultivation) to each crop, proper planting and harvesting timings, and the allocation of human resources and equipment needed for planting the crops. Improper crop planning will eventually affect the downstream activities; hence, cropping decisions play an important role in shaping the whole agro-food supply chain.

Globally, sugar is produced from both beet and cane. The strategic importance of the sugar sector comes from its crucial role in managing land and water usage, securing food, and providing rural employment opportunities. As reported, sugar beet is currently the cheapest sugar source and lowest in water usage, as well as being an effective biomass source (Kolfschoten, Bruins, & Sanders, 2014). Thus, the sugar beet sector is an important area where minimizing the total supply chain cost given the growing scarcity of water supplies would have a significant contribution and an important economic impact.

The different agro supply chain activities could be classified into three main stages: agricultural, transportation and industrial stages. As shown in Fig. 1, the supply chain of sugar beet includes the following activities:

- Cultivation activities: many challenges should be considered to implement a successful cropping plan for sugar beet. Beets should not be planted on the same plot for three or four successive years (Asadi, 2006). It means that beets require to be grown in a rotation to preserve the crops' yield and land's soil. Crop rotation is defined as "the repeatable scheme of planting different crops in a predetermined

* Corresponding author at: Department of Industrial and Manufacturing Engineering, Egypt-Japan University for Science and Technology, Alexandria, Egypt.
E-mail addresses: Ibrahim.fikry@ejust.edu.eg, Ibrahim.fikry@eng.asu.edu.eg (I. Fikry).

https://doi.org/10.1016/j.cie.2021.107300

Available online 8 April 2021
0360-8352/

sequence in the same parcel of land, in an effort to reduce the use of synthetic fertilizers and pesticides" (Zegada-Lizarazu and Monti, 2011).

- Harvesting/picking activities: sugar content is the main indicator for determining the quality of beets. Harvesting decisions should consider the maximum sweetness level for the fresh picked produce (Jonkman, Barbosa-Póvoa, & Bloemhof, 2019). Moreover, the freshly-picked produce begins a respiration process which requires a high level of coordination to transport, store, and process the beet within a very narrow time window (Kolfschoten et al., 2014).
- Transportation activities: the next important stage is to transport the harvested crops from farms to the processing facilities (i.e. facilities which process the beets into final products such as white sugar). Ineffective transportation will impact production costs by disrupting the production plans through excess or lack of supply depending on the delivered quantities (Jonkman, Barbosa-Póvoa, et al., 2019).
- Processing and storage activities: the final stage in the supply chain is related to sugar extraction from sugar beet and the separation of sugar from other materials (e.g. tare, molasses), which is referred to the sugar conversion process, the output from such process can calculate the sugar conversion factor (ton/ton). This stage starts with storing the fresh beet in a large storage area with quantities that ensures that the processing facility will run at its full capacity. However, storing the sugar beet for long time affects its perishability and results in a reduced sugar conversion factor (Asadi, 2006), which in turn affects the supply and demand over the supply chain. Therefore, industrial decisions should be aligned with the supply and demand sides.

The integrated production logistics problem in the sugar beet supply chain is a complex problem. Inappropriate decisions will affect the entire supply chain, that is why the integration between the cropping, transportation and industrial decisions is essential to maximize supply chain profitability while considering appropriate level of responsiveness.

The different terminologies specific to the problem and used in this paper are as follow:

- Plot: a piece of land used to plant different crops.
- Farm: consists of a certain number of plots.
- Processing facility: converts the fresh crops into finished products.
- Product: The manufactured substance after undergoing a standard production process.

This paper presents a complete formulation and solution for the integrated production-logistics-crop rotation problem of sugar beet supply chain. A mathematical model is proposed with the objective of minimizing the total transportation and storage costs, while considering the specific characteristics of the agro-food supply chain to produce sugar. Sugar is considered as the main output (i.e. final product) from the sugar beet. A novel time dimension is added to the proposed model to allow more than a single cropping season. Explicitly considering temporal variations into supply chain decisions is mainly important in agriculture related decisions, in which preserving the natural resources is essential. The main purpose of the proposed model is to identify the optimal rotation schedules in a restricted area, which will affect the supply of crops to the processing facilities during the rotation cycle. The proposed model is divided into two main parts; the agriculture related decisions (i.e. crop rotation decisions) and production-logistics related decisions.

The paper is organized as follows, in Section 2, a literature review for the problem is addressed. The problem description is illustrated in Section 3, and the proposed mathematical model for the integrated production-logistics-crop rotation problem is given in Section 4. Section 5 presents the computational results, and finally Section 6 gives the conclusions and the directions for future work.

2. Literature review

The literature review is divided into two sub-sections. The first, discussing the crop rotation problem and its related work. The second discusses agro-food supply chain models focusing on integrated problems.

2.1. The crop rotation problem

The articles discussing the crop rotation problem have significantly

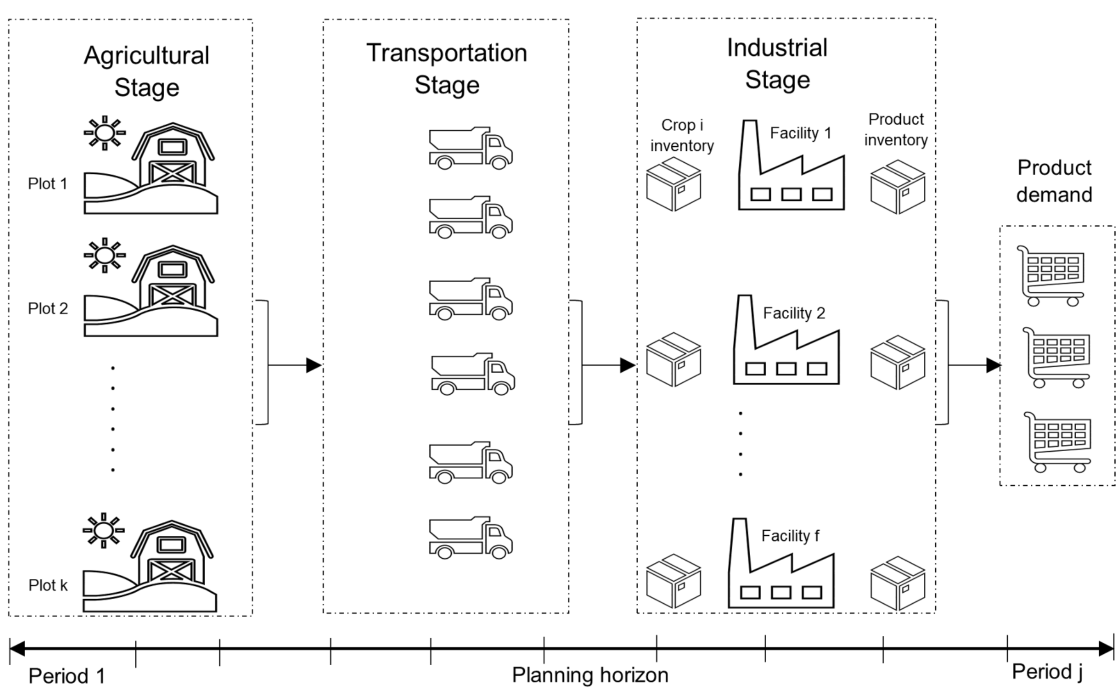

Fig. 1. Production logistics activities for the sugar supply chain.

Table 1
Previous literature reviews on agro-food supply chains.

Author (s)	Main Objectives
(Ahumada & Rene Villalobos, 2009)	Modelling of different planning models in AFSC, focusing on the production and distribution of fresh produce crops.
(Zhang & Wilhelm, 2011)	Identified the decision support models according to the specialty crops (fruits, vegetables, grapes and wine…etc.). A wide variety of disciplines and modelling techniques were investigated depending on the specialty crop.
(Shukla & Jharkharia, 2013)	Review the literature regarding the agri-fresh produce with a framework covering all the major operational issues. The aim is to shade a light on the opportunities for more integration, and collaboration within the entire supply chain.
(Kusumastuti, Van Donk, & Teunter, 2016)	A comprehensive study for all the integrated models, which include harvesting, processing, and inventory control planning. Models' characteristics were discussed based on mapping different Agri-chains activities.
(Borodin et al., 2016)	Evaluate the main uncertain parameters in the agricultural sector. Highlight new operations research advances for handling uncertainty and the widely used frameworks in the agricultural supply chain management problems.
(Zhu et al., 2018)	A comprehensive review of the Sustainable Food Supply Chain (SFSC), while considering the economic, environmental and social issues in SFSC.
(Behzadi et al., 2018)	A review for the quantitative decision models used in the agricultural supply chain with main focus on risk management related issues.
(Kamble, Gunasekaran, & Gawankar, 2019)	Understand the use of big data, the internet of things, and blockchain technologies in the agriculture supply chains. The main purpose is to plan for building sustainable data-driven agriculture supply chains.

increased in the last few years (Filho & Angelo, 2019; Fikry, Gheith, & Eltawil, 2019). The general objective of the majority of them was generating optimal performance related to two main areas: economics and agronomy. One comprehensive review that covered the modelling approaches used in crop rotation and cropping planning decisions can be found in (Dury et al., 2012). This combinatorial problem involves several factors that may include but not restricted to: succession of crops, irrigation amount, fallow periods, market demand, and space limitation. The classification of the following review is based on the solution method to derive practical cropping plans.

(Alfandari, Plateau, & Schepler, 2015) proposed a Branch-and-Price-and-Cut (BPC) algorithm with the aim of covering the seasonal demand and minimizing the space consumption. The work is based on an earlier Mixed Integer Programming (MIP) model that used for the crop rotation planning problem with a constraint on cultivating or fallowing a plot (Alfandari et al., 2011).

(Ridier, Chaib, & Roussy, 2016) developed a dynamic stochastic model to support crop rotation decisions. The objective was to maximize the income over the planning horizon while considering the crop's yield and market risks. The results of the model indicated that higher risks in the production and the market demand tend to discourage the farmer to utilize long rotations.

(Li et al., 2015) developed a heuristic to achieve the objectives of maximizing the prices and minimizing the profit differences in contract farming between farmers by identifying the optimal rotation schedule. (Filho & Angelo, 2019) proposed a binary nonlinear optimization model for the sustainable crop rotation, they solved the linearized version along with a metaheuristic. A constructive heuristic and a genetic algorithm were used as approximate methods, which outperformed the linearized model in large instances.

Life Cycle Assessment (LCA) was involved in a multi-stage MILP model for exploring the crop rotation schemes and defining the optimal performance within a planned time window in (Capitanescu et al., 2017).

(dos Santos et al., 2011) proposed a binary optimization model to study the crop rotation problem for multiple plots for the organic vegetable crop production. The model is decomposed using Dantzig-Wolfe decomposition and a column generation-based heuristic was used to solve it. In each rotation, the optimal decisions for maximizing the land usage were explored while considering the succession of crops, neighborhood restrictions, leguminous planting, and recovery period. A further modification was considered by adding constraints on the crop yield, demand, and nature of each available plot(dos Santos et al., 2010).

Researchers discussed the agronomic and the economic values of the crop rotation problem. The interested reader is referred to (Dogliotti, Rossing, & Van Ittersum, 2003; Detlefsen and Jensen, 2007; Schönhart, Schmid, & Schneider, 2011)for more models in crop rotation.

Based on the existing literature, crop rotation optimization is found to have a significant impact on the overall performance of agricultural systems. That is why it is attracting growing interest. On the other hand, it should be coupled with industrial decisions to optimally manage the whole agro-food supply chain.

2.2. Agro-food supply chain

The subject of Agro-Food Supply Chain (AFSC) is well established in the literature with many review articles discussing the different perspectives of its unique criteria. The main contribution of such review articles is shown in Table 1.

Economic, environmental, and social objectives were considered among others in studying the AFSC. Regarding economic objectives, profit maximization is one of these objectives. For example, (Flores et al., 2019) aimed at maximizing the net profit in terms of quantity and quality of the supplied crops, they proposed an integrated supply chain planning model that considers the harvesting activities. Also, cost minimization is one of the economic objectives. For example, (Mogale et al., 2017) used an improved ant colony metaheuristic to minimize the total cost, which involves the transportation, storage, and operational costs of a food grain supply chain. Furthermore, (Jonkman, Barbosa-Póvoa, et al., 2019) considered both of the above-mentioned objectives simultaneously along with the environmental and social objectives.

In the fresh produce supply chain, where the only process after harvesting is packaging before delivering the products to warehouses and/or distribution centers. (Ahumada & Rene Villalobos, 2011a) presented a tactical model for the integrated production and distribution problem of tomatoes with two important constraints; perishability and decay in quality due to the storage of crops. They explored short term planning decisions for the same problem by formulating an operational model designed to integrate the harvesting, packaging, and distribution activities (Ahumada & Rene Villalobos, 2011b). Similar approach was followed to introduce a stochastic version of the earlier tactical model with uncertainty in yield and price (Ahumada, Villalobos, & Mason, 2012).

In the context of sugar industry, there are limited papers related to the sugar beet processing and most of the studies focused on the sugar cane. Table 2 shows a summary of some related studies for sugar processing from sugar cane and sugar beet. After investigation, it could be concluded that there are three studies available for sugar processing from sugar beet, however; all these studies investigated the sugar beet supply chain from the strategic level perspective. (Jensen, Münster, & Pisinger, 2017) presented a mixed integer programming model for a biogas supply chain, where sugar beet is used as a feedstock to the biogas plant. They proposed a network flow model to simulate the chain from the farms to the energy demand markets.

Many attempts have been reported to model the integrated production and logistics problems for several sectors such as fruits, citrus, and grains. In the specific case of sugar beet, the overall optimization of its

Table 2
Sugar processing industry related papers.

Author (s)	Decisions	Objective	Country
(Grunow, Günther, & Westinner, 2007)	A	Formulation of MILP model for solving an integrated cultivation planning and harvest scheduling problem. The model was solved by hierarchical decomposition approach, where each stage was optimized separately.	Venezuela
(Paiva & Morabito, 2009)	I	Selection of the industrial processes for producing sugar, ethanol, and molasses. The main decision variables include the crushed quantities of sugarcane, suppliers selection for sugarcane and its transportation, and the strategy of storing the final product.	Brazil
(Jena & Poggi, 2013)	A	A mathematical model that considers the tactical and operational decisions. It considers the cultivation and harvest integrated problem with maximization of sugar content during harvesting.	Brazil
(Jonkman et al., 2017)*	I	Selection of process design to find the optimal supply chain configuration in the sugar beet processing industry.	Netherland
(Jonkman, Kanellopoulos, & Bloemhof, 2019)*	A,I	Exploring the design of biobased supply chains, while considering the crop rotation constraints. The optimum strategic supply network configuration was selected based on economic and environmental objectives.	Netherland
(Carvajal, Sarache, & Costa, 2019)	A,I	Development of an agro-industrial supply chain model to maximize cane yield and evaluate the performance of a biofuel production plant.	Colombia
(Jonkman, Barbosa-Póvoa & Bloemhof, 2019)*	A,I	Considered the economic and environmental strategic issues in a model for designing agro-food supply chains, taking into account the harvesting and quality decay parameters.	Netherland

A: Agricultural I: Industrial.
* Papers related to sugar beet processing.

supply chain is not attained. Previous research considered only the strategic decisions as a performance measure for the overall beet supply chain (Jonkman et al., 2017; Jonkman, Barbosa-Póvoa, et al., 2019; Jonkman, Kanellopoulos, & Bloemhof, 2019). That's why, it is important to propose an integrated decision support tool that considers different planning levels.

To fill this gap, this paper presents a strategic-tactical planning model formulation for integrating the critical agricultural decisions with logistics and processing decisions for sugar beet. The model aims to minimize the total cost along the sugar beet supply chain. The model can determine the optimum quantities of beets delivered to the sugar processing facility while considering the best quality level for the delivered quantities.

3. Problem description

The value of sugar beet is measured by its sugar content, and it varies significantly during the harvesting periods, and depends on the temperature and humidity. These circumstances require efficient planning and logistics control to transport and process the harvested beets to minimize sucrose losses. Tactical planning decisions are related to the size of the planted areas, harvesting plans, transporting beets from agricultural fields to factories, processing, as well as managing inventories and transportation of the final products to warehouses.

Proper tactical planning of sugar beet processing industry can solve and settle any conflicts between the different supply chain stages. The main tactical decisions faced by the industry are shown in Fig. 2. Improper upstream decisions for the agricultural stage will affect the downstream decisions of the production stage. Hence, a high level of coordination is needed to drive smoothly the sugar beet supply chain and to optimize the associated costs.

The coordination of the planning of crop rotation, harvesting, transportation, and processing decisions is needed to effectively control the sugar beet supply chain. This sector has interlinked characteristics, whereby these characteristics have some implications as follows:

1. Sugar beet should be grown according to a crop rotation cycle, where a time gap is needed before replanting it again. It is usually planted after a cereal crop (e.g. wheat) and other crops might be also chosen.
2. Long-term storage is not permitted due to the temperature effect, which means that, harvesting should be correctly planned and conducted on as-needed basis (Asadi, 2006).
3. The delivered beets must be processed within a narrow time window to reduce sugar loss, so production plans must be aligned with harvesting schedules. Considerable attention to transportation planning should be paid especially for a seasonal crop such as sugar beet, where its campaign typically lasts for 3–4 months in most countries. This situation means that the processing capacity is almost tripled in order to process the harvested beet.
4. The beet is transported over long and varied distances due to the rotation constraints, therefore transportation cost will fluctuate among years for centralized processing facilities. A study in the

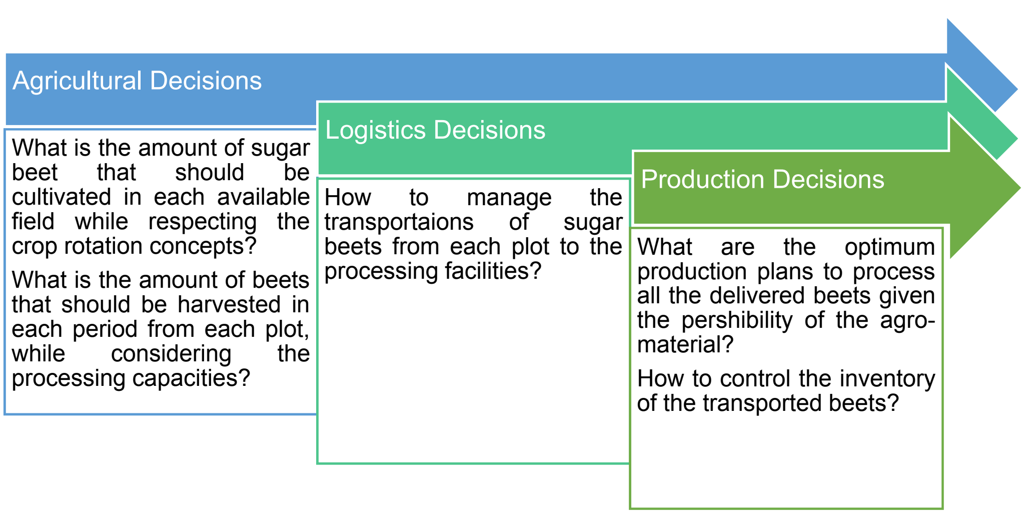

Fig. 2. Sugar Beet processing industry Decisions.

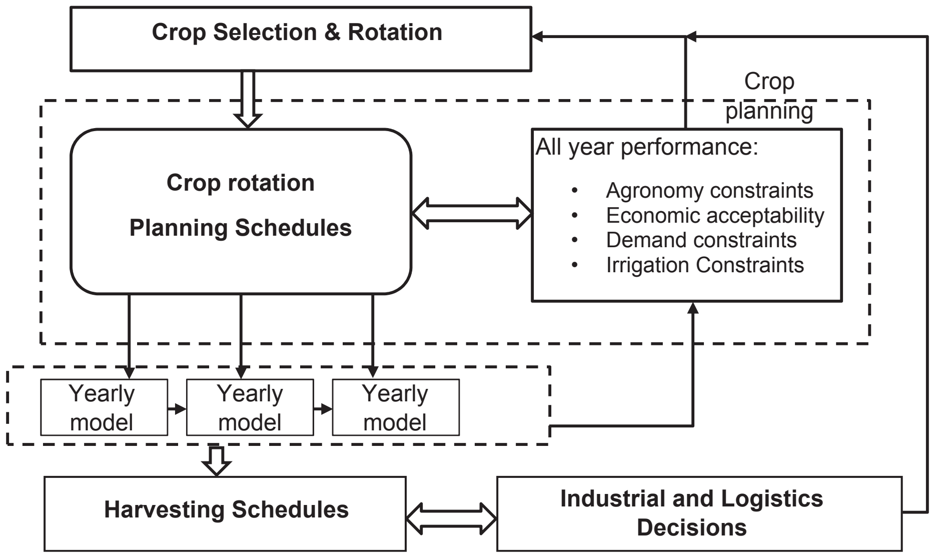

Fig. 3. The proposed framework for the integrated model.

Netherlands reported that the transportation cost of beet contributed to approximately 50% of the total cost (Kolfschoten et al., 2014).

So, there is a need to set proper farming plans for the owned lands as well as a high level of coordination with farmers in case of contract farming. This means that, beets should be transported over varied distances each year within the rotation cycle compared to other crops such as cane, which could be planted using a monocropping approach. Since a single crop is grown yearly in monocropping technique without the need to introduce a rotation between multiple crops.

The sugar producers must secure a sufficient supply of sugar beets each season while minimizing the differences in costs between seasons. These differences are mainly due to the variability in the transportation cost. Therefore, products' prices are function of the associated transportation costs for the implemented crop rotation schedule.

All the mentioned aspects make the integrated production and logistics tactical planning problem for sugar beets a complex and challenging task. This study presents a conceptual scheme for the integrated production-logistics-crop rotation planning problem faced by sugar beet processing industry and proposes a linear programming model that includes agricultural, production and transportation decisions. The proposed framework that describes the integrated model is presented in Fig. 3.

4. The proposed integrated production-logistics-crop rotation planning model

The proposed deterministic binary model considers multi-period agriculture planning decisions, as well as the integrated strategic crop rotation planning problem, as well as the tactical industrial decisions.

In this section, the proposed model is mapping the flow from farms to the processing facilities. The model seeks to achieve the following:

- Selecting the land to be planted (i.e. plot) each season
- Determining the harvested quantity each period.
- Calculating the transported quantity from each farm per period.
- Estimating the total stored quantity inside the processing facility

4.1. Model assumptions

1. The estimated yield for each crop in each plot is known, it depends on the harvested period and its maturation level.
2. The field consists of homogenous plots with standard sizes, hence the obtained yield of the desired crop is the same regardless the plot used to plant that crop.
3. The expected crop yield and irrigation water do not depend on the preceding crop, but on the present crop.
4. The total annual available water is constant for all the years in the rotation cycle.
5. Each crop has a known deterministic demand, which is satisfied at the end of the harvesting period.
6. There is no stored water in the soil.
7. After harvesting, the harvested quantity is transported directly to the processing facility.
8. The transported quantity is processed within a limited time period to minimize the deterioration of crop quality.
9. Inventory is held at the processing facilities. No inventory is held at the fields.
10. Demand is known and constant for each period and could be supplied to the customer at the end of each time period.
11. Plants (i.e. processing facilities) have a fixed processing capacity.

4.2. Model nomenclature

i	$\in I$	Set of crops
j	$\in J$	Set of time periods
k	$\in K$	Set of plots
t	$\in T$	Set of years in the rotation cycle
h_{it}	$\subseteq J$	Allowable harvesting periods for crop i at year$t$
f_N	$\in N$	Set of crops' families where f_{N-1} and f_N represents the legumes family and fallow periods (i.e. unplanted periods), respectively.
v	$\in V$	Set of vehicles
f	$\in F$	Set of facilities
p	$\in P$	Set of products

Parameters:

S_{it}	Starting period of planting crop i in year t, where $S_{it} \in J$
tp_i	Required production time of crop$i$
E_{it}	Ending period of harvesting crop i in year t, where $E_{it} \in J$
N	Number of crops' families
YLD_{ijk}	Expected harvested percentage of crop i harvested in period j at plot k (%)
B_{it}	Minimum number of plots assigned to crop i in year$t$
AP	Number of available plots per year
W_i	Required water for irrigating crop i (m^3/ha)
AW	Total annual available water (m^3)

(continued on next page)

(continued)

f_i	Planting frequency of crop i during the rotation cycle
fm_i	Frequency modification factor for crop$i$
T	Length of rotation cycle in years (years)
F_i	The reciprocal of frequency of crop$i$
TS	Annual time slots
PS	Number of different planting seasons per year
TP_{ik}	Optimum yield quantity of crop $i$planted in plot k (ton/ha)
$MT_{i_{min}}$	Minimum maturation period for crop i, $MT_{i_{min}} \subseteq h_{it}$
$MT_{i_{max}}$	Maximum maturation period for crop i, $MT_{i_{max}} \subseteq h_{it}$
$TCAP_v$	Truck capacity for transporting crops using vehicle v (ton)
N_{max_k}	Maximum number of trips to plot$k$
V_{vj}	Total number of trips for vehicle$v$ during period$j$
S_{ijf}^{max}	Maximum required supply of crop i in period j to facility$f$ (ton/period)
PC_{pjf}	Processing capacity of product p in period j in facility f (ton/period)
CF_{pf}	Conversion factor for producing product p in facility f (ton/ton)
D_{pjf}	Demand of product p in period j at facility f (ton)
d_{kf}	Distance between plot k and facility f (km)
C_{iv}	Cost per km of transporting crop i using vehicle v (€/ km. ton)
h_{ijf}	Holding cost of crop i in period j in facility f(€. period / ton)
h_{pjf}	Holding cost of product ρ in period j in facility f(€. period / ton)

Decision variables:

The decision variables in this model are classified into independent and dependent variables as follows:

- Independent decision variables:

$$X_{ijk}\begin{cases} 1 & if\ crop\ i\ is\ planted\ in\ period\ j\ in\ plot\ k, \\ 0 & otherwise \end{cases}$$

$$Z_{ijk}\begin{cases} 1 & if\ crop\ i\ is\ harvested\ in\ period\ j\ in\ plot\ k, \\ 0 & otherwise \end{cases}$$

- Dependent decision variables:

NT_{ijkfv}	Required number of trips to transport crop$i$ harvested in period j from plot k to facility f using vehicle$v$
SQ_{ijkfv}	Shipped quantity of crop i harvested in period j from plot k to facility$f$ using vehicle$v$
PP_{pjf}	Processed quantity of product p in period j in facility$f$
I_{ijf}	Inventory of crop i in period j at facility$f$
IP_{pjf}	Inventory of product p in period j at facility$f$

For better understanding of the proposed formulation, Fig. 4 illustrates the inter-dependencies between the decision variables of the agricultural and the production stages. The model's objective is to minimize the total cost of production and logistics activities in the sugar beet processing industry, while considering the effect of multi-period on the rotation cycle.

Objective function

The objective function minimizes the total cost elements associated with the harvested quantity. It includes transportation costs from different plots to the processing facilities, and the inventory holding cost at the facilities for both agro-material and finished products.

$$min \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{f=1}^{F}\sum_{v=1}^{V} d_{kf}.C_{iv}.SQ_{ijkfv} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{f=1}^{F} h_{ijf}.I_{ijf} + \sum_{p=1}^{P}\sum_{j=1}^{J} \times \sum_{f=1}^{F} h_{pjf}.IP_{pjf}$$

4.3. Model formulation

In the proposed model, the constraints are classified into three categories. Crop rotation related constraints, harvesting and transportation related constraints, and inventory and processing related constraints.

4.3.1. Crop rotation constraints

An agricultural area is divided into a set of plots. Each plot could be cultivated with various types of crops. The following criteria are considered:

- Each crop has its own criteria which include: the planting and harvesting dates, and the associated demand.
- Each crop requires different amounts of water for irrigation that must be satisfied at a given time period.
- Crops belong to different botanic families. Crops from the same family cannot be planted in succession.
- The integration of legumes with other crops in the same rotation cycle positively affects the soil and hence the obtained yield.
- Every cycle should involve one or more fallow periods to allow the soil to restore its moisture and fertility content.

The first type of constraints encountered represent the necessary conditions for implementing a successful crop rotation for the planted crops. Constraints (1) and (2) ensure that, there would be at most one crop per plot per period, and that the planted crop will occupy the plot during its production cycle, respectively.

$$\sum_{i=1}^{I} X_{ijk} \leq 1 \quad \forall j \in J, k \in K \tag{1}$$

$$\sum_{j=S_{it}}^{E_{it}} X_{ijk} = tp_i.X_{ijk} \quad \forall i \in I, k \in K, t \in T \tag{2}$$

Constraint (3) guarantees that each crop is only grown in its planting period (i.e. each crop will be planted in its right planting period).

$$\sum_{k=1}^{K}\sum_{j \in J/\{S_{it},\ldots,E_{it}\}} X_{ijk} = 0 \quad \forall i \in I, t \in T \tag{3}$$

Constraint (4) prevents the same crop or two crops from the same family to be planted consecutively so as to implement a successful crop rotation cycle.

$$X_{ijk} + \sum_{tp_i}\sum_{i \in f_n} X_{i(j+tp_i)k} \leq 1 \quad \forall i \in I, j \in E_{it}, k \in K, n = 1, \cdots N-2 \tag{4}$$

Constraint (5) ensures that there is enough time before planting the same crop again, while constraint (6) ensures that the number of

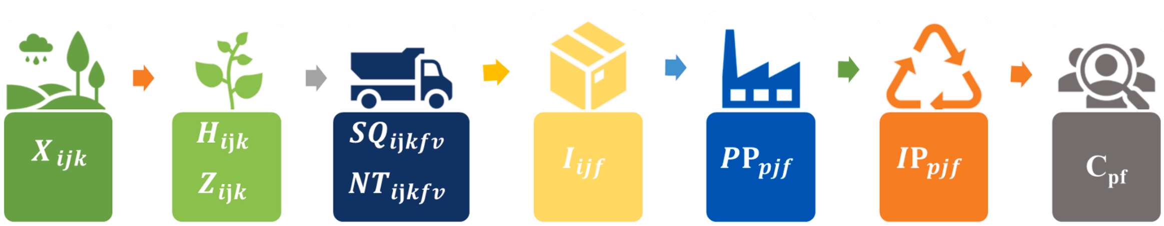

Fig. 4. Scheme of the decision variables for Sugar beet PL problem.

occurrence of each crop is based on the crop's frequency during the rotation cycle. It is worth noting that constraint (6) will be enough to represent the crops' frequencies without introducing constraint (5) in case that the rotation length is less than or equal to the frequency reciprocal of the crops.

$$\sum_{j=1}^{F_i} X_{i(S_{it}+(j-1)TS)k} \leq 1 \quad \forall i \in I, k \in K \tag{5}$$

$$\sum_{S_{it}} X_{iS_{it}k} \leq T.f_i + fm_i \quad \forall i \in I, k \in K \tag{6}$$

For convenience, a binary dependent variable Y_{ikt} is introduced in constraint (7), to determine the annual status of crop *i* planted in plot *k* in year *t*.

$$Y_{ikt} - X_{is_{it}k} = 0 \quad \forall i \in I, k \in K, t \in T, \tag{7}$$

Constraint (8) ensures that at most a certain number of crops are planted per year for each plot.

$$\sum_{i=1}^{I} Y_{ikt} \leq PS \quad \forall k \in K, t \in T \tag{8}$$

Constraint (9) limits the yearly planted crops to the total available lands. While constraint (10) represents the minimum number of required plots for each crop so as to satisfy the demand during the rotation cycle

$$\sum_{i}^{I} \sum_{k=1}^{K} Y_{ikt} \leq PS.AP \quad \forall t \in T \tag{9}$$

$$\sum_{k=1}^{K} Y_{ikt} \geq B_{it} \quad \forall i \in I, t \in T \tag{10}$$

Constraints (11) and (12) consider the presence of at least one legume crop during the rotation cycle and fallow during the rotation cycle, respectively.

$$\sum_{i \in f_{N-1}} \sum_{t=1}^{T} Y_{ikt} \geq 1 \quad \forall k \in K \tag{11}$$

$$\sum_{i \in f_N} \sum_{t=1}^{T} Y_{ikt} \geq 1 \quad \forall k \in K \tag{12}$$

Constraint (13) ensures that the total used water for irrigation does not exceed the total available amount of water.

$$\sum_{i=1}^{I} \sum_{k=1}^{k} W_i.Y_{ikt} \leq AW \quad \forall t \in T \tag{13}$$

Constraints (1)–(13) represent the crop rotation related constraints. These constraints integrate the crop rotation problem with temporal and spatial variations, while considering the operational constraints. The output from these sets of constraints could determine the crops' sequences and the allocated area for each crop simultaneously, which represents the area required for cultivating the permissible sequence of crops within a specific rotation cycle.

4.3.2. Harvesting and transportation constraints

Constraint (14) ensures that the total harvested quantity per plot occurs once if and only if a crop was planted in a certain plot in year t.

$$\sum_{MT_{i_{min}}}^{MT_{i_{max}}} Z_{ijk} = Y_{ikt} \quad \forall i \in I, k \in K, t \in T \tag{14}$$

Constraint (15) represents the harvested quantity for each crop in terms of the maturation period as a percentage of total planted quantity.

$$H_{ijk} = YLD_{ijk}.TP_{ik}.Z_{ijk} \quad \forall i \in I, \ j \in h_{it}, \ k \in K \tag{15}$$

Constraint (16) estimates the required number of truck trips to transport the harvested quantity from plot k to facility f. Constraint (17) limits the number of trips to each plot to a certain value during its harvesting period. Constraint (18) sets a limit for the total number of trips for each vehicle during each time slot

$$\sum_{v=1}^{V} NT_{ijkfv}.TCAP_v \geq H_{ijk} \quad \forall i \in I, j \in h_{it}, k \in K, f \in F \tag{16}$$

$$\sum_{j \in h_{it}} \sum_{v=1}^{V} NT_{ijkfv} \leq N_{max_k} \quad \forall i \in I, k \in K, f \in F \tag{17}$$

$$\sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{f=1}^{F} NT_{ijkfv} \leq V_{vj} \quad \forall j \in h_{it}, v \in V \tag{18}$$

Constraint (19) allows the shipping of the harvested quantity to the processing facilities from the planted plot in that period. It is necessary to couple the total quantity from the harvested plot with the shipped quantity to the processing facilities.

$$H_{ijk} = \sum_{f=1}^{F} \sum_{v=1}^{V} SQ_{ijkfv} \quad \forall i \in I, j \in h_{it}, k \in K \tag{19}$$

4.3.3. Inventory and processing constraints

In Eq. (20), the total shipped quantity for each crop during each harvesting period is limited to the maximum available storage in each facility.

$$\sum_{k=1}^{K} \sum_{v=1}^{V} SQ_{ijkfv} \leq S_{ijf}^{max} \quad \forall i \in I, j \in h_{it}, f \in F \tag{20}$$

Constraints (21) and (22) ensure that the processed quantity for each product does not exceed the facility's production capacity, and the processed quantity for each product satisfies the demand per each time slot, respectively.

$$PP_{pjf} \leq PC_{pjf} \quad \forall p \in P, j \in J, f \in F \tag{21}$$

$$PP_{pjf} \geq D_{pjf} \quad \forall p \in P, j \in J, f \in F \tag{22}$$

Constraint (23) determines the available quantity from each crop in each facility at each time period according to the total shipped quantity and the available inventory from the last period. Constraint (24) determines the available inventory for each crop at each time period in each facility.

$$AV_{ijf} = \sum_{k=1}^{K} \sum_{v=1}^{V} SQ_{ijkfv} + I_{i(j-1)f} \quad \forall i \in I, j \in h_{it}, f \in F \tag{23}$$

$$I_{ijf} = AV_{ijf} - \frac{PP_{pjf}}{CF_{pf}} \quad \forall i \in I, j \in J, p \in P, f \in F \tag{24}$$

Constraint (25) associates the processed quantity with the yield of each product according to the total available quantity at each time period

$$PP_{pjf} \leq CF_{pf}.AV_{ijf} \quad \forall i \in I, p \in P, j \in J, f \in F \tag{25}$$

Constraint (26) determines the available inventory from each product at each time period in each facility. The accumulated non-processed quantities from different regions are stored in order to be processed according to plant's capacity within the following time period to meet a certain demand.

$$IP_{pjf} = PP_{pjf} + IP_{p(j-1)f} - D_{pjf} \quad \forall p \in P, j \in J, f \in F \tag{26}$$

Finally, The non-negativity nature of the decision variables and

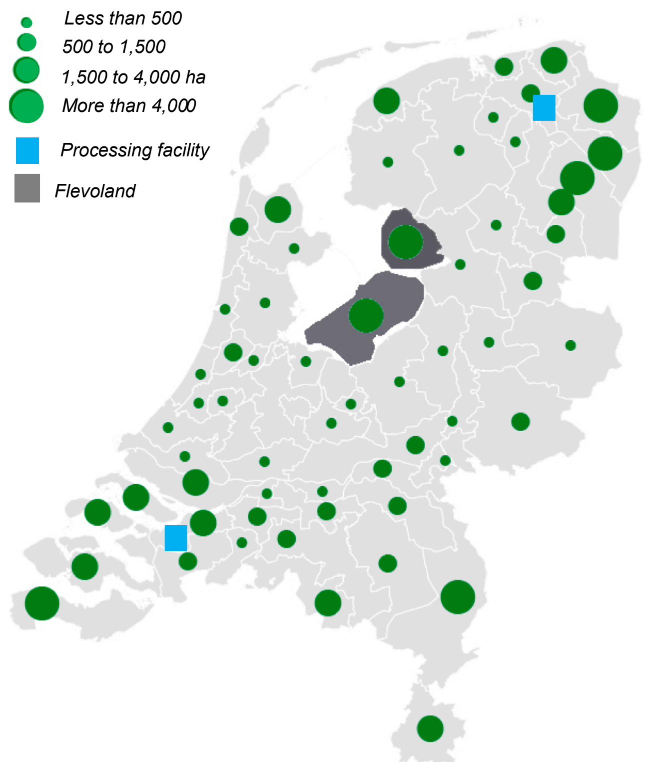

Fig. 5. Sugar beet Farmlands and processing facilities in the Netherlands, 2017 based on (CBS, 2020).

binary representations.

$$X_{ijk} \in \{0,1\} \quad \forall i \in I \quad j \in J \quad k \in K$$

$$Y_{ikt} \in \{0,1\} \quad \forall i \in I \quad k \in K \quad t \in T$$

$$Z_{ijk} \in \{0,1\} \quad \forall i \in I \quad j \in h_{it} \quad k \in K$$

$$NT_{ijkfv} \geq 0 \quad \forall i \in I \quad j \in h_{it} \quad k \in K \quad f \in F \quad v \in V$$

$$H_{ijk} \geq 0 \quad \forall i \in I \quad j \in h_{it} \quad k \in K$$

$$SQ_{ijkfv} \geq 0 \quad \forall i \in I \quad j \in h_{it} \quad k \in K \quad f \in F \quad v \in V$$

$$AV_{ijf} \geq 0 \quad \forall i \in I \quad j \in J \quad f \in F$$

$$PP_{pjf} \geq 0 \quad \forall p \in P \quad j \in J \quad f \in F$$

$$I_{ijf} \geq 0 \quad \forall i \in I \quad j \in J \quad f \in F$$

$$IP_{pjf} \geq 0 \quad \forall p \in P \quad j \in J \quad f \in F$$

5. Computational results

In this section, the solution of the proposed binary programming model is presented, with reference to instances from real data. A structured case from Netherlands is adopted.

5.1. Data and instances description

The required data for the optimization model was obtained from Flevoland province, Netherlands. It consists of six municipalities as shown in Fig. 5. In Netherlands, the processing facilities are centralized in the shown locations, where Flevoland supply the northern facility located in Groningen (Unie, 2011). For the agricultural stage, different crops belonging to seven families are selected for the study.

Sugar beet can only be grown every four years based on the used rotation schemes by farmers (Asadi, 2006). A planning horizon of four years (i.e. is divided into weeks) was used in the computational analysis. A single green manure crop and at least one fallow period were adopted for each area at each rotation schedule. Crop data is listed in Table 3 as well as production parameters (i.e. planting and harvesting dates, and crop's frequency).

After the harvesting of each crop based on its maturation, the harvested quantity should be transported directly to the processing facility. In the transportation stage, the traveled distance varies according to the location of the arable area (i.e. plot where the crop has been harvested) with respect to the processing facility's location. The distance was measured from the center point of municipality's location to the center point of the processing facility's location, it was obtained from (Jonkman et al., 2017).

Due to the difficulty of obtaining a real distance for each farm inside the studied area. It was assumed that the location of the plots follows a normal distribution with a mean equal to the center point of the municipality, with standard deviation of 10 Km. and 15 Km. for the two studied municipalities. For more details please refer to the digital supplementary material. A homogeneous fleet of vehicles is used for transporting the harvested quantity, the transportation cost and parameters as well as processing data are indicated in Table 4.

In the processing stage, there are many processing facilities' configurations with different product portfolios (Jonkman et al., 2017). The traditional facility configuration for converting sugar beet to white sugar as a final product was selected along the structured case study. The traditional configuration is widely existed worldwide and that's why it was selected in this study.

In the previous section, a binary integer programing model has been presented for the integrated production-logistics-crop rotation problem. Before implementing the proposed model in the presented case, several instances for the integrated planning problem were generated to check the performance of the proposed model as shown in Table 5. Different

Table 3
Data for different crops in Flevoland, obtained from (a) (Mandryk et al., 2014) (b) (Wolf et al., 2010).

No.	Crop	Family	f_i^a (#.yr-1)	Yield[a] (tons/ha)	Sowing date[b]	Harvesting date[b]	Maturity period[b] (Days)
1	Sugar beet	Chenopodiaceae	1/4	90–100	April	Oct. -Nov.	285–305
2	Winter wheat	grass (Cereal)	1/4	8.7	Sept. – Oct.	Aug.	210–230
3	Green peas	Legumes	1/6	5.7	March	Nov.	300–315
4	Seed potato	Nightshade	1/4	38.7	March - April	July – Sept.	220–230
5	Seed onion	Amaryllidaceae	1/6	37	March	June-July	215–235
6	Winter rapeseed	Brassica	1/4	3.5	Jan.	Dec.	300–315
7	Barley (spring)	grass (Cereal)	1	6.3	April	Sep.	215–235
8	Maize (silage)	grass (Cereal)	1	40.8	April	Nov.	275–295
9	Onions	Amaryllidaceae	1/6	58.4	March	July-August	235–250
10	Potatoes (ware)	Nightshade	1/3	56.8	March - April	Aug – Sept.	255–275
11	Wheat (spring)	grass (Cereal)	1/2	7.8	April	Sept.	215–235
12	Winter carrot	Apiaceae	1/6	70	Sept.-Oct.	Jan.	70–80

Table 4
Transportation and processing related parameters (a) (Kolfschoten, Bruins, & Sanders, 2014) (b) (Jonkman, Barbosa-Póvoa, et al., 2019) (c) (Jonkman et al., 2017).

Parameter	Value
Transportation cost [a]	0.1 €/ton.km
Truck capacity	50 ton
Holding cost of processed products [b]	0.1 €.day/ton
Holding cost of Sugar beet	0.15 €.day/ton
White sugar conversion rate [a]	0.14625
Daily processing capacity [c]	10 Kton

Table 5
Generated problem instances.

Category	Instance	I	J	T	K	V	P	F
Small scale	1	5	192	4	12	1	1	1
	2	12	192	4	12	1	1	1
	3	5	192	4	48	1	1	1
	4	12	192	4	48	1	1	1
	5	5	192	4	100	1	1	1
	6	12	192	4	100	1	1	1
Medium scale	7	5	192	4	1000	1	1	1
	8	12	192	4	1000	1	1	1
	9	5	192	4	2000	1	1	1
	10	12	192	4	2000	1	1	1
	11	5	192	4	5000	1	1	1
	12	12	192	4	5000	1	1	1
Large scale	13	5	192	4	8000	1	1	1
	14	12	192	4	8000	1	1	1
	15	5	192	4	10,000	1	1	1
	16	12	192	4	10,000	1	1	1

combinations of crops (I), periods (J), rotation years (T), plots (K), vehicles (V), and facilities (F) were evaluated during the computational analysis. The model was implemented using GUROBI 9.0 and tested on a 3.47 GHz Intel Xeon with 96 GB RAM computer.

5.2. Results and discussion

In this section, the instances have been solved using the recommended settings in GUROBI for solving a Binary Integer Programming (BIP) model with some parameters tuning to reduce the running time. The default settings consider multiple solvers simultaneously and choose the algorithm that finishes first. This concurrent technique is time and memory consuming especially with a complex model. The effect of parameters tuning on the performance of the original model is illustrated in Table 6. The instances with parameter tuning are solved faster. The CPU time obtained on the tuned BIP is extremely reduced for the proposed model compared to the default settings, which will be discussed in this subsection.

The formulated model was tested with the previous instances. A series of experiments were considered to analyze the performance of the proposed model. Sixteen instances were tested, with a varying number of crops, plots and vehicles. The possible number of crop schedules grows exponentially with the considered number of periods and plots. The computational time increases as the problem size increases. In particular, the increase in the number of binary variables due to the periodically selected crops, which forms a hard to solve problem (e.g. knapsack problem) (dos Santos et al., 2010).

Table 6
An illustrative example for parameter tuning.

Instance	Tuned settings			Default settings		
	Obj.	Time (sec.)	Gap (%)	Obj.	Time (sec.)	Gap (%)
2	9401	0.12	0	9401	0.45	0
4	38,374	1.4	0	38,374	249.37	0
6	79,121	70.87	0	79,205	3245	0.1

Table 7
Results for the proposed model.

Instance	Objective	Gap (%)	Computation time (sec.)	Row	Column
1	9401	0	0.12	6,377	17,495
2	9401	0	0.2	7,528	36,851
3	38,374	0	0.84	23,873	67,967
4	38,374	0	1.4	28,372	145,031
5	79,121	0	32.6	49,145	140,871
6	79,121	0	70.87	58,480	301,291
7	778,267	0	37.38	486,545	1,402,671
8	778,278	0.1	41.66	579,580	3,005,791
9	1,551,430	0	49.87	972,545	2,804,671
10	1,551,430	0	107.9	1,158,580	6,010,791
11	3,869,918	0	205.11	2,430,545	7,010,671
12	3,852,150	0.4	697.38	2,895,580	15,025,791
13	7,566,010	0.2	6178.96	3,960,545	11,216,671
14	7,562,628	0.1	2373.32	4,632,580	24,040,791
15	10,010,000	0	675.55	2,140,540	2,770,671
16	10,010,004	0	2745.82	5,790,580	30,050,791

Table 7 presents the results for the BIP model. For each instance, the table lists the size of the problem, the objective function value, the computation time, and the obtained gap (%). As shown in the table, the formulated model was solved to optimality, where a detailed agricultural plan for all the plots could be monitored and controlled.

The solver was able to obtain the optimum solutions within a reasonable time for most of the instances. However, a long computational time occurred for large instances, where optimality comes at a cost of time.

In addition to the discussed implications above, the mathematical model was used to solve up to 10,000 plots, where the harvested beet plots in Flevoland reach a similar value (CBS, 2020). For the group of instances ($I = 5$), the selected crops for the analysis were the strategic crops (wheat, sugar beet, onions and potatoes) beside one legume crop.

In these circumstances, each crop is representing a different family, so the succession of crops from the same family could be relaxed without affecting the solution. In general, the number of variables grows exponentially with the considered number of crops, plots, and periods. The primary objective is to explore the effects of different number of plots, crops, and vehicles on the complexity of the problem.

From the computational experiments, the number of plots has a clear effect on the computational time. Indeed, the larger the number of plots, the higher the cost obtained. The optimal solution is independent of the number of crops, as the beet was selected for cropping regardless the number of competitive crops.

One of the most important aspects that the model considers, is the crop rotation schedules which will be discussed in details in the next subsection.

5.2.1. Crop rotation schedules

The presented model incorporates all the necessary conditions (e.g. water, demand) to successfully implement appropriate rotation schedules. The crop planning and scheduling problem is used to identify the schedules for the different crops, such that the production of each crop at each period is adequate to satisfy its corresponding demand. In many situations, the selected schedule intends to maximize the farmer's profit, while respecting a set of ecological conditions and biological criteria. These methods include planting, growing and harvesting constraints alongside the restrictions on the succession of certain crops, and finally the essential presence of fallow and green manures in a specific manner.

The detailed cropping plan for large farms (<2000 ha) could be obtained by solving the proposed model. As reported in (Mandryk et al., 2014), the average size of a small farm in Netherlands is less than 20 ha. In this subsection, a farm with 12 plots was considered for exploring the rotation schedules through different farm's plans. Three scenarios have been investigated, according to the crops' demand requirement. Each scenario could be summarized as:

- Scenario 1: Satisfying a certain demand (e.g. contract farming).
- Scenario 2: Presence of each crop on a yearly basis during the rotation cycle (crop mix).
- Scenario 3: Cultivation of the strategic crops (e.g. wheat, sugar beet, seed onions and potatoes) at least once per year in any plot, to achieve self-sufficiency of these crops.

In the first scenario, the farmer can assign at most three hectares for sugar beet (i.e. 25% share of the owned plots). In particular, the farmer would be encouraged to grow beet on a regular basis during the rotation cycle. Fig. 6 illustrates the obtained schedule for the first scenario, where the sugar beet will be planted in plots 2, 3, and 12 in the first year and repeated in different plots across the entire rotation cycle.

The second scenario will urge the farmer to either make trade-off between the crops or increase the owned plots. However, this scenario is not favored by farmers as they prefer to plant a certain number of crops, but it shows the suggested sequence of planting the crops. The sequence of the crops for the second scenario is shown in Fig. 7. The results suggest that crops from different families can be planted while respecting agronomic constraints.

The third scenario illustrates current practice in farm planning, where the soil fertility is guaranteed by fertilizers rather than introducing a legume crop in the rotation cycle. In this scenario, constraint (11) was relaxed to remove legume restriction on the rotation cycle. The obtained schedule is shown in Fig. 8, and it was compared with the rotation schemes in (Mandryk et al., 2014). The suggested schedules are consistent with their currently implemented practices. The field information during the rotation schedule can be easily overseen, hence the operational tasks can be planned as well.

5.2.2. Sensitivity analysis

One of the advantages of linear programming is performing sensitivity and what-if analysis. In practice, data related to agricultural sector have uncertain values, so performing a simple scenario analysis will highlight any changes in the objective function value. The sensitivity of the result has been carried out on a medium size problem. Nonetheless, the effects of the below-mentioned perspectives will remain the same regardless the size of the problem.

5.2.2.1. Crop yield and sugar content. Further analysis of the proposed model for different levels of crop yield was performed. This is due to the observed fluctuations in the beet yield per hectare based on the historical data. The total expected yield was varied from the original yield value between an increase of 20%, and a decrease of 50%, respectively. The findings presented in Fig. 9 show that an increase in transportation cost is observed for a lower percentage of yield.

Lower yield allows expanding the cultivation of plots to maintain the same level of supply to the processing facility. In that case, the shipped quantity should be transported from larger number of plots compared to the original case, which in turns increase the total transportation cost. Thus, to obtain lower transportation cost, crops with higher yield should be targeted.

The extracted white sugar produced by the traditional configuration is usually depending on the sugar contents of the supplied beets. Sugar extraction may deviate during the sugar production with an average conversion rate listed in Table 4 in the ideal conditions. For the sake of illustration, the expected sugar conversion was altered by successive increases and decreases of 20% from their average to infer its impact on the objective value.

An anticipated finding was that an increase in the conversion factor should cause a high reduction in the total cost as shown in Fig. 10. In comparison between the two discussed analysis, the conversion factor has a significant impact on the cost when compared to effect of the crop yield. This is why most of companies are creating an incentive schemes to the famers who supply sugar beet with high sucrose content.

5.2.2.2. Harvesting decisions. As explained earlier, the delivery of beet is usually stretched out for ensuring and maintaining a reasonable supply to the industrial facilities during the beet campaign. The total cost can be affected by the uncertainties in the sugar beet supplies associated with the harvesting decisions. Meanwhile, the right harvesting time is controlled by temperature and the allowable storage time of the sugar beet. Hence, a further investigation is needed to indicate the effect of different harvesting scenarios on the total cost.

The shipped quantity from farm to the processing facility could be scheduled according to the following schemes. Three different harvesting plans were considered to indicate the impact of changing the harvesting schedules on the total cost. Firstly, creation of schedules based on harvesting along the campaign. For the first scenario, some limitation may be raised for extending the harvesting periods due to the temperature condition (e.g. Frost). Secondly, early harvesting for late processing where the delivered beets are piled for further operations. Lastly, proper harvesting plans within a limited time window.

On that occasion, three scenarios were analyzed to see the effect of changing the harvesting policy on the total cost (Fig. 11). As observed, the upward trend of the cost in scenario 2, which indicates that the total cost will be increased with higher expected inventory levels. Thus, it will be less attractive for decision makers than the other two scenarios. An opportunity could be found in decreasing the total cost as it is highly affected by scenarios 1 and 3. Therefore, the harvesting policy could be one of these scenarios or a combination of the previous mentioned scenarios, which have a similar influence on the total achieved cost.

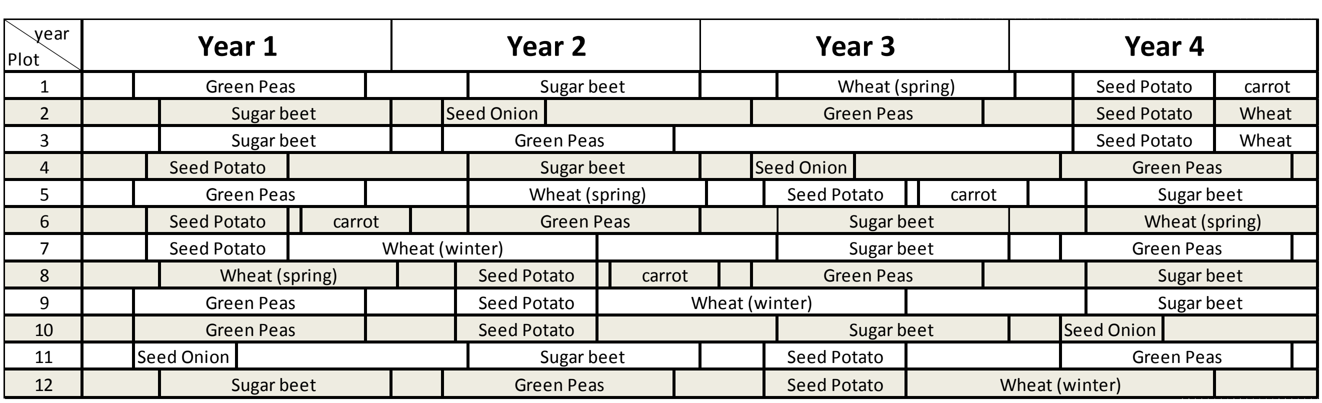

Fig. 6. Crop production schedule throughout the planning horizon for all plots for the first scenario.

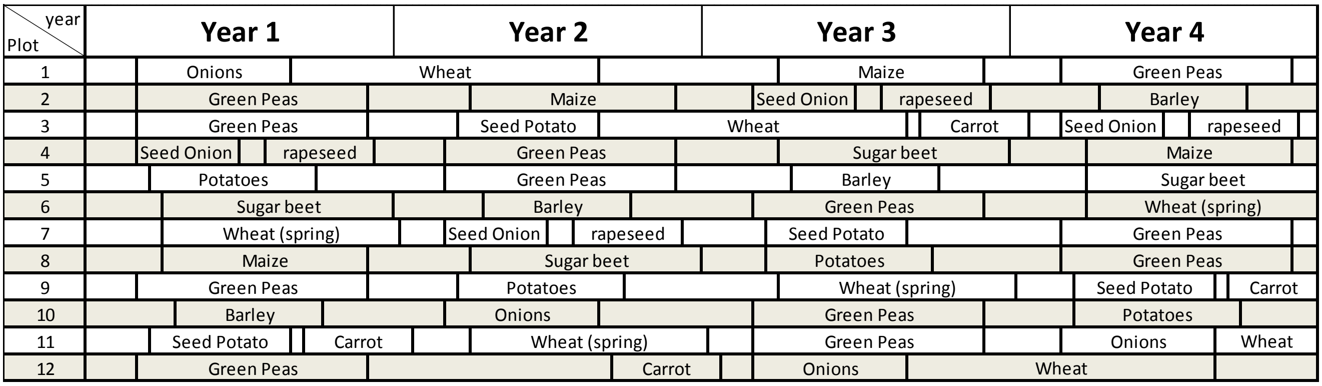

Fig. 7. Yearly crop mix schedules throughout the planning horizon.

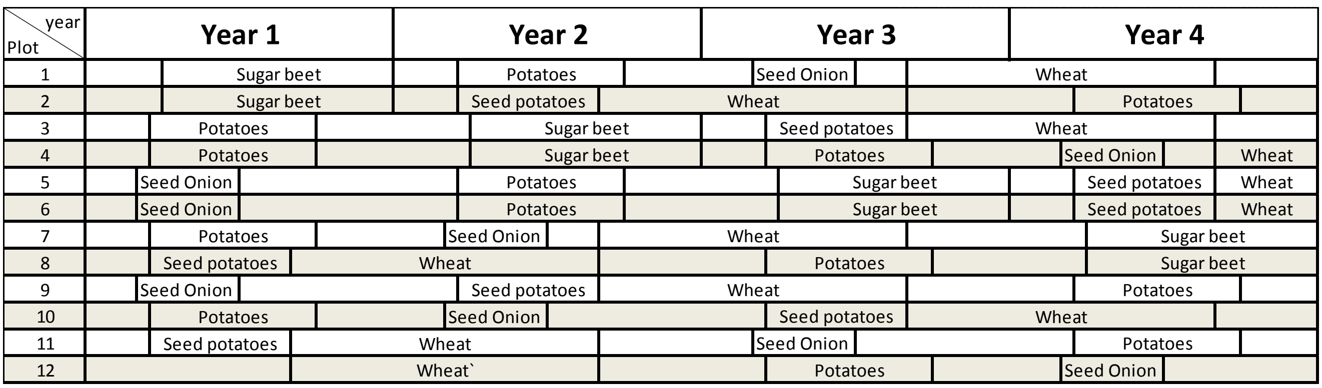

Fig. 8. Crop production schedules throughout the planning horizon for the third scenario.

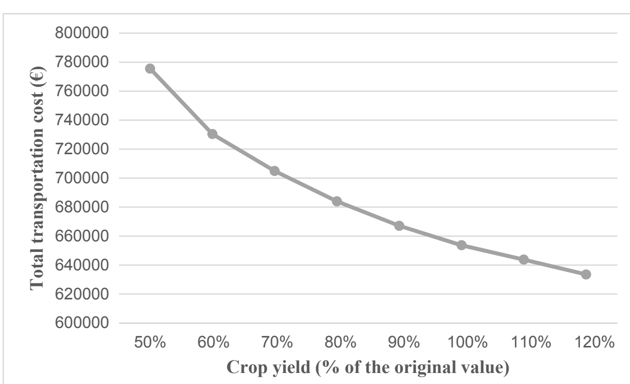

Fig. 9. Sensitivity of the result for increasing the crop yield.

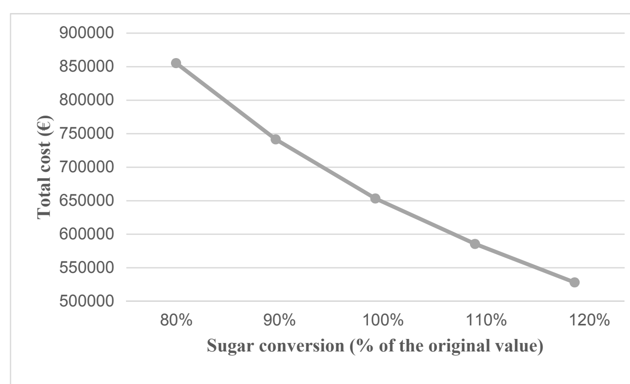

Fig. 10. The total cost value due to changes in the sugar conversion factor.

6. Conclusion

This paper aims to develop a deterministic integer optimization model to optimally solve the production and logistics planning problem of the sugar beet processing industry, as well as briefly describe a specific case in the Dutch context. The integrated chain starts from the farmer and ends with a certain sugar demand. An analysis of production logistics costs, crop planning for sugar beet, and industrial planning were performed to represent the annual key decisions making parameters. One of the key expected contributions of this study is introducing a practical analytical model for planning the agricultural and industrial activities. On the other hand, its practical application to solve real production-logistics problem and take uncertainty of relevant data in the sugar beet sector.

The main contribution of this paper is developing a decision support tool for the tactical planning problem in the sugar beet industry. A unique time dimension was added to represent the rotation planning horizon, where this additional dimension allows crop rotation planning between different cropping seasons. In this regard, the proposed model integrates crop rotation and industrial decisions on a tactical level. Furthermore, this model emphasizes the total economic analysis by highlighting the critical cost factors associated with the sugar-beet processing industry.

In contrast to the reviewed articles, a strategic-tactical model combines all the needed operation constraints in any agriculture system was introduced. These constraints are coupled with transportation and processing activities to optimize the related decisions. A set of different generated scenarios was considered to solve a real production logistics

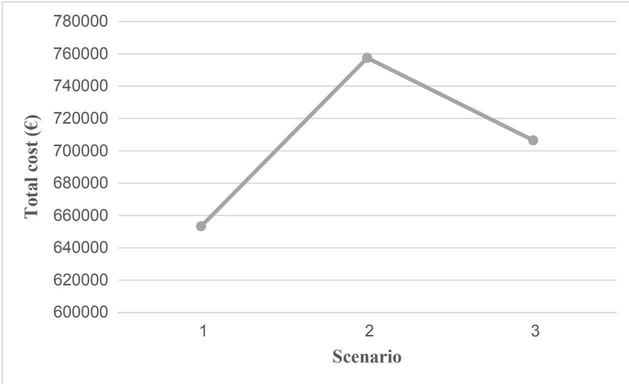

Fig. 11. Impact of different harvesting scenarios on the total cost value.

planning problem. The proposed model can be used as a supporting tool by the industry experts. The model has been applied to a real case study for monitoring the crop yield, its acreage, and different harvesting schedules in order to reduce the associated risks in the sugar industry.

As a future research, exploration of other solution alternatives to decrease the computational time required by larger instances. These instances made the planning problem very time consuming. Some challenges remain in the computational analysis leading to extend the exact methods with heuristics. Hence, a potential investigation into approaches that reduce the model size and the model run-time will facilitate the interaction between the decision makers and the model support tool. Additionally, the size of the problem with its huge integer solutions could be optimized by the relaxed mixed integer programming (RMIP) (Jensen et al., 2017). A further investigation using decomposition algorithms, and hybrid heuristics might make this problem easier to solve.

CRediT authorship contribution statement

I. Fikry: Conceptualization, Software, Investigation, Formal analysis, Writing - original draft. **Mohamed Gheith:** Writing - review & editing, Supervision, Validation. **Amr Eltawil:** Writing - review & editing, Supervision, Validation.

Acknowledgement

This research project was supported by the Egyptian ministry of higher education grant and the Japanese International Cooperation Agency (JICA) in the scope of the Egypt-Japan University of Science and Technology.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cie.2021.107300.

References

Ahumada, O., & Rene Villalobos, J. (2009). Application of planning models in the agri-food supply chain: A review. *European Journal of Operational Research, 196*(1), 1–20.
Ahumada, O., & Rene Villalobos, J. (2011a). A tactical model for planning the production and distribution of fresh produce. *Annals of Operations Research, 190*(1), 339–358.
Ahumada, O., & Rene Villalobos, J. (2011b). Operational model for planning the harvest and distribution of perishable agricultural products. *International Journal of Production Economics, 133*(2), 677–687.
Ahumada, O., Rene Villalobos, J., & Nicholas Mason, A. (2012). Tactical planning of the production and distribution of fresh agricultural products under uncertainty. *Agricultural Systems, 112*, 17–26.
Alfandari, L., Lemalade, J.-L., Nagih, A., & Plateau, G. (2011). A MIP flow model for crop-rotation planning in a context of forest sustainable development. *Annals of Operations Research, 190*(1), 149–164.
Alfandari, L., Plateau, A., & Schepler, X. (2015). A branch-and-price-and-cut approach for sustainable crop rotation planning. *European Journal of Operational Research, 241*(3), 872–879.
Aliano Filho, A., de Oliveira Florentino, H., Pato, M. V., Poltroniere, S. C., & da Silva Costa, J. F. (2019). Exact and heuristic methods to solve a Bi-objective problem of sustainable cultivation. *Annals of Operations Research*, 1–30.
Asadi, M. (2006). *Beet-sugar handbook*. John Wiley & Sons.
Behzadi, G., O'Sullivan, M. J., Olsen, T. L., & Zhang, A. (2018). Agribusiness supply chain risk management: A review of quantitative decision models. *Omega, 79*, 21–42.
Borodin, V., Bourtembourg, J., Hnaien, F., & Labadie, N. (2016). Handling uncertainty in agricultural supply chain management: A state of the art. *European Journal of Operational Research, 254*(2), 348–359.
Capitanescu, F., Marvuglia, A., Navarrete Gutiérrez, T., & Benetto, E. (2017). Multi-stage farm management optimization under environmental and crop rotation constraints. *Journal of Cleaner Production, 147*, 197–205.
Carvajal, J., Sarache, W., & Costa, Y. (2019). Addressing a robust decision in the sugarcane supply chain: introduction of a new agricultural investment project in Colombia. *Computers and Electronics in Agriculture, 157*, 77–89.
CBS (2020). Central Bureau Voor de Statistiek.
Detlefsen, N. K., & Jensen, A. L. (2007). Modelling optimal crop sequences using network flows. *Agricultural Systems, 94*(2), 566–572.
Dogliotti, S., Rossing, W. A. H., & Van Ittersum, M. K. (2003). ROTAT, a tool for systematically generating crop rotations. *European Journal of Agronomy, 19*(2), 239–250.
Dury, J., Schaller, N., Garcia, F., Reynaud, A., & Bergez, J. E. (2012). Models to support cropping plan and crop rotation decisions. A review. *Agronomy for Sustainable Development, 32*(2), 567–580.
Fikry, I., Gheith, M., & Eltawil, A. (2019). A new formulation and solution for the crop rotation planning problem. *Proceedings of international conference on computers and industrial engineering, 2019-Octob.*.
Flores, H., Rene Villalobos, J., Ahumada, O., Uchanski, M., Meneses, C., & Sanchez, O. (2019). Use of supply chain planning tools for efficiently placing small farmers into high-value, vegetable markets. *Computers and Electronics in Agriculture, 157*, 205–217.
Grunow, M., Günther, H. O., & Westinner, R. (2007). Supply optimization for the production of raw sugar. *International Journal of Production Economics, 110*(1–2), 224–239.
Jena, S. D., & Poggi, M. (2013). Harvest planning in the Brazilian sugar cane industry via mixed integer programming. *European Journal of Operational Research, 230*(2), 374–384.
Jensen, I. G., Münster, M., & Pisinger, D. (2017). Optimizing the supply chain of biomass and biogas for a single plant considering mass and energy losses. *European Journal of Operational Research, 262*(2), 744–758.
Jonkman, J., Barbosa-Póvoa, A. P., & Bloemhof, J. M. (2019). Integrating harvesting decisions in the design of agro-food supply chains. *European Journal of Operational Research, 276*(1), 247–258.
Jonkman, J., Bloemhof, J. M., Van der Vorst, J. G. A. J., & van der Padt, A. (2017). Selecting food process designs from a supply chain perspective. *Journal of Food Engineering, 195*, 52–60.
Jonkman, J., Kanellopoulos, A., & Bloemhof, J. M. (2019). Designing an eco-efficient biomass-based supply chain using a multi-actor optimisation model. *Journal of Cleaner Production, 210*, 1065–1075.
Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2019). Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications. *International Journal of Production Economics*.
Kolfschoten, R. C., Bruins, M. E., & Sanders, J. P. M. (2014). Opportunities for small-scale biorefinery for production of sugar and ethanol in the Netherlands. *Biofuels, Bioproducts and Biorefining, 8*(4), 475–486.
Kusumastuti, R. D., Donk, D. P. V., & Teunter, R.u. (2016). Crop-related harvesting and processing planning: A review. *International Journal of Production Economics, 174*, 76–92.
Li, J., Rodriguez, D., Zhang, D., & Ma, K. (2015). Crop rotation model for contract farming with constraints on similar profits. *Computers and Electronics in Agriculture, 119*, 12–18.
Mandryk, M., Reidsma, P., Kanellopoulos, A., Groot, J. C. J., & van Ittersum, M. K. (2014). The role of farmers' objectives in current farm practices and adaptation preferences: A case study in Flevoland, the Netherlands. *Regional Environmental Change, 14*(4), 1463–1478.
Mogale, D. G., Dolgui, A., Kandhway, R., Kumar, S. K., & Tiwari, M. K. (2017). A multi-period inventory transportation model for tactical planning of food grain supply chain. *Computers & Industrial Engineering, 110*, 379–394.
Paiva, R. P. O., & Morabito, R. (2009). An optimization model for the aggregate production planning of a Brazilian sugar and ethanol milling company. *Annals of Operations Research, 169*(1), 117.
Ridier, A., Chaib, K., & Roussy, C. (2016). A dynamic stochastic programming model of crop rotation choice to test the adoption of long rotation under price and production risks. *European Journal of Operational Research, 252*(1), 270–279.
dos Santos, L. M. R., Mara, A. M., Costa, M. N., Arenales, M. N., & Santos, R. H. S. (2010). Sustainable vegetable crop supply problem. *European Journal of Operational Research, 204*(3), 639–647.
dos Santos, L., Rodrigues, M., Michelon, P., Arenales, M. N., & Santos, R. H. S. (2011). Crop rotation scheduling with adjacency constraints. *Annals of Operations Research, 190*(1), 165–180.
Schönhart, M., Schmid, E., & Schneider, U. A. (2011). CropRota – A crop rotation model to support integrated land use assessments. *European Journal of Agronomy, 34*(4), 263–277.

Shukla, M., & Jharkharia, S. (2013). Agri-fresh produce supply chain management: A state-of-the-art literature review. *International Journal of Operations & Production Management*.

Unie, S. (2011). Long-term stability of the european sugar sector, Also after 2015; Position Paper Dutch Sugar Sector.

Wolf, J., Mandryk, M., Kanellopoulos, A., van Oort, P.A.J., Schaap, B.F., Reidsma, P., Van Ittersum, M.K. (2010). Methodologies for analyzing future farming systems in flevoland as applied within the AgriAdapt Project. Wageningen UR.

Zegada-Lizarazu, W., & Monti, A. (2011). Energy crops in rotation. A review. *Biomass and Bioenergy, 35*(1), 12–25.

Zhang, W., & Wilhelm, W. E. (2011). OR/MS decision support models for the specialty crops industry: A literature review. *Annals of Operations Research, 190*(1), 131–148.

Zhu, Z., Chu, F., Dolgui, A., Chu, C., Zhou, W., & Piramuthu, S. (2018). Recent advances and opportunities in sustainable food supply chain: A model-oriented review. *International Journal of Production Research, 56*(17), 5700–5722.